AD-A036 601 STANFORD UNIV CALIF W W HANSEN LABS OF PHYSICS F/G 20/5

FREE ELECTRON LASER.(U)

DEC 76 J M MADEY, H A SCHWETTMAN F44620-75-C-0070

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W. W. Hansen Laboratories of Physics
Stanford University
Stanford, California 94305

Free Electron Laser

FINAL REPORT

AIR FORCE CONTRACT: F44620-75-C-0070

See 1473

For the Period:

15 February, 1975 to 14 July, 1976

CO-PRINCIPAL INVESTIGATORS:

J. M. J. Madey and H. A. Schwettman

December, 1976

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFOSR - TR - 77 - 0091	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 FREE ELECTRON LASER.		5. TYPE OF REPORT & PERIOD COVERED FINAL REPORT
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Madey, J. M. Schwettman, H. A.		8. CONTRACT OR GRANT NUMBER(s) 15 F44620-75-C-0070 New
9. PERFORMING ORGANIZATION NAME AND ADDRESS Stanford University Stanford, California 94305		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 16 611021 9768-02NE 17 02
11. CONTROLLING OFFICE NAME AND ADDRESS AFOSR/NE Bolling AFB, Washington DC		12. REPORT DATE 1976
		13. NUMBER OF PAGES 56
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 9 Final rept. 15 Feb 75 - 14 Jul 76		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited 18 AFOSR

11 Dec 76 12 58p. 19 TR-77-0091

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

10 John M. J. Madey
H. A. Schwettman

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The objective of this program is the determination of the characteristics and capabilities of laser amplifiers and oscillators based on the stimulated emission of radiation by free electrons in a spatially periodic magnetic field. The previous effort in this program was directed towards the measurement of the single pass gain and the dependence of the gain on electron energy and current, the electron beam radius and divergence, and the amplitude of the magnetic field.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE UNCLASSIFIED

408572 SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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This document constitutes the final scientific report for the period 15 October, 1975 to 14 July, 1976.

The objective of this program is the determination of the characteristics and capabilities of laser amplifiers and oscillators based on the stimulated emission of radiation by free electrons in a spatially periodic magnetic field. The previous effort in this program was directed towards the measurement of the single pass gain and the dependence of the gain on electron energy and current, the electron beam radius and divergence, and the amplitude of the magnetic field. The results of this effort are summarized in the previous reports and publications (see Phys. Rev. Letts. 36, p. 717, 1976).

The program is motivated by the potential of this class of device for tuneable operation at high power and high efficiency. The prospects were reviewed in detail at the Quebec Synchrotron Radiation Conference in May, 1976. A copy of the conference manuscript is enclosed.

While the experimental results have largely substantiated our understanding and expectations, several important characteristics could not be evaluated in the single pass gain measurements. These measurements yielded only a lower bound on the power density for saturation and no information was obtained regarding the statistical fluctuations in the energy lost by the electrons in the interaction region. The statistical fluctuations, in particular, will play an important role in the operation of this class of device at high power and theoretical estimates of the effect differ. It is clearly important to acquire some experimental data on these effects.

Data on these effects would be obtainable form a low power "single pass" oscillator in which the electron beam would make a single pass through the interaction region. Other useful information could be obtained from the oscillator and an oscillator of this type could also serve as a useful source of radiation for spectroscopy, material science, and photochemistry. These reasons constitute the rational for our efforts in this period.

The work accomplished during this period included (1) the design and construction of a laser oscillator based on the magnet used in the earlier single pass gain measurements, (2) the operation of the oscillator below threshold and the evaluation of the performance of the components of the oscillator including the measurement of the losses of the oscillator's optical resonator, (3) the design of a system to raise the peak current of the accelerator to the value required for operation of the oscillator above threshold, and (4) the development of a theoretical technique based on Feynman's path integral for the analysis of laser operation in the large signal regime.

<u>Oscillator Design and Construction</u>: Development of the oscillator involved the development of an optical resonator to provide feedback around the interaction region within the helical magnetic field and the development of a system to transport the electron beam from the electron beam line to the optical axis within the interaction region.

The oscillator design is indicated schematically in Figure 1 and a photo of the system appears in Figure 2. The resonator design was based on the calculations of Abrams,[1] Degman and Hull,[2] and consist of a pair of 6.6 meter radius spherical mirrors spaced approximately 3 meter from the ends of the interaction region. The design follows from the circumstance that at 10μ radiation propagating through the 10.5 mm copper tube enclosing the interaction region is constrained by the conducting walls to assume the form of a waveguide mode. The resonator was designed to minimize losses for radiation in the fundamental EH_{11} mode.

The resonator mirrors were mounted on NRC honeycomb tables. The orientation of the mirrors and the length of the resonator could be set remotely from the control room. Retractable mirrors were provided within the interaction region to couple the radiation from the TEA laser to the optical axis. It was thus possible to measure the gain during the oscillator experiments using the same techniques as in the earlier single pass gain experiments. Also, a CO_2 plasma tube was installed in the resonator. The system could thus be operated as a conventional laser oscillator to check the resonator alignment.

In the earlier single pass gain measurements the optical axis was coincident with the electron beam line. For the oscillator the helical magnet was translated one meter from the beam line and it was necessary to design a magnet system to deflect the electron beam from the beam line onto the optical axis. This was accomplished by means of a pair of iron core chicane magnets. As in the earlier experiments, air core coils were

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1 R. L. Abrams, IEEE J. Quantum Elect. 8, 838 (1972).

2 J. J. Degman and D. R. Hall, IEEE J. Quantum Elect. 9, 901 (1973).

used as verniers to steer the beam to the laser experiment and to center the beam in the interaction region.

Operation of the Oscillator: Tests of the apparatus were conducted using an accelerated electron beam in January 1976. A 24 MeV beam was transported through the interaction region and measurements were made of the total power and spectrum of the radiation from the oscillator. The experiment revealed several problems with the beam transport system and the resonator including loss of current on the beam position monitoring foils and susceptibility of the resonator to vibration. The optical characteristics of the resonator were established using the CO_2 plasma tube. The CO_2 amplifier provided sufficient gain to bring the system above threshold independent of the electron beam. Thus, the resonator mode pattern could be studied with the electron beam off. Also, the gain of the amplifier was measured as a function of plasma tube current; the current required to cross threshold with the plasma tube within the resonator yields a value of the resonator losses.

The resonator loss was much larger than anticipated and a major effort was undertaken to identify the mechanism(s) responsible. The loss per pass for the waveguide resonator was estimated theoretically at 3% . This is the sum of the 1% mirror transmission, the theoretical diffraction losses of 2% and the waveguide attenuation estimated from the optical constants for copper to be less than 0.5%. The measured loss for the system is approximately 16% .

We have measured the loss associated with each component of the resonator. The difference between the theoretical and measured resonator losses can be accounted for by the attenuation and mode conversion in the copper waveguide. The waveguide attenuation was measured by focussing the TEA CO_2 laser to a 3.3 mm waist at the entrance to the guide. The arrangement couples 98% of the incident power to the EH_{11} waveguide mode. Measurements were made of the total incident power and the power emerging from this guide. A theodolite was used to align the optical axis with the waveguide axis. The position and angle of the incident beam were trimmed after alignment to minimize attenuation. The measured attenuation for the 6 meter tube length was 8% . This is an order of magnitude greater than the loss estimated from the optical constants for copper. Measurements have also been conducted of the attenuation in a 2 meter straight section of copper tube of the same diameter and type as the tube lining the magnet bore. There was no measureable attenuation.

The observed attenuation in the magnet bore must evidently be related either to the condition of the surface of the waveguide or the curvature of the bore. We have measured the absorption coefficient for 10 μ radiation at grazing incidence on copper. At an angle of incidence of 50 milliradians the absorption coefficient for burnished OFHC copper is 2% . This increased to 10% when the reflecting surface was coated with an oil film or a heavy oxide layer. The absorption returned to a low value following removal of the oil film with an aceton saturated swab.

It seems unlikely that the excess attenuation can be attributed to the surface. Prior to the attenuation measurements, the bore was thoroughly swabbed with Freon TC and acetone to remove any soluble organic contamination and purged with dry air. While no attempts have been made to chemically remove the observed light oxide layer, the same preparation resulted in low measured loss in the 2 meter test section.

The most probable source of attenuation is the curvature of the bore. The bore has been surveyed at 30 centimeter intervals with an estimated precision of ± 0.05 mm. While the waveguide bore is reasonably straight within the interaction region, it is noticeably arced at the two ends. While the bore deviates from a straight line by less than 0.25 mm within the magnet winding the deviation exceeds 0.50 mm in the 60 centimeters nearest the ends. The corresponding radius of curvature is estimated at 400 meters.

Curvature is known to result in high losses for the EH_{11} mode in metallic waveguides. The loss calculated for the observed curvature is 20% which agrees in order of magnitude with the observed loss of 8% .

The curvature of the waveguide has another effect in that power initially coupled to the EH_{11} mode is converted to higher order modes. Our measurements indicate that approximately 10% of the power emerging from the waveguide is in the higher order modes. The estimate was generated by measuring the power density of the radiation emerging from the waveguide and numerically calculating the overlap of the observed distribution and the expected gaussian output beam.

Mode conversion is a serious problem because the resonator diffraction losses for the higher order modes are large. Mode conversion therefore represents another loss channel: power directed from the EH_{11} mode by mode conversion in the waveguide will be lost from the resonator.

The measured losses are sufficient to account for the observed resonator loss. If we assume that all the power in the higher order modes is lost to diffraction in reflection from the resonator mirrors, the sum of the losses due to waveguide dissipation, mode conversion and mirror transmission yields a loss of 19% per pass, close to the observed value of 16%.

It is unlikely that the waveguide curvature can be corrected. The curved sections at the ends of the waveguide are partially imbedded in semi-rigid epoxy and there seems to be no practical means to straighten the tube. We believe the measured resonator loss to be the minimum attainable loss for this system.

The primary effect of the resonator loss is to raise the electron current required for operation above threshold. Since no gain is available for radiation propagating anti-parallel to the electron beam while loss is suffered in both directions, the electron beam must supply a gain of at least 32% per pass to cross threshold. At 10 μ we have observed a gain of 7% per pass at an electron current of 70 mA. Operation of the oscillator at 10 μ therefore requires a minimum electron current of 320 mA. This exceeds the capability of the accelerator with the standard electron gun.

A high current gun is clearly required.

The problems with the resonator are directly traceable to the diameter of the waveguide bore. A minimum diameter bore was originally selected in the design of the magnet to secure the highest possible field on axis. We now know from the experiment that useful gain can be obtained at a relatively modest magnetic field. A bore diameter larger by a factor of two than the present design would be a practical choice. A gaussian beam at 10 μ would propagate without distortion through a 2 cm bore assuming the bore length does not exceed 6 meters. An optical resonator of conventional design could then be used and losses would be limited only by the characteristics of the resonator mirrors.

High Current Gun Design: The calculated electron current required for operation above threshold exceeds the current available on a cw basis. The limits to the accelerated beam current for the superconducting accelerator are set by the available RF power and by space charge effects in the 100 kV injector. Under cw conditions, space charge effects are not a factor and the current is limited by the available power. This is a limitation on the average current and therefore an increase in the peak current can be obtained by modulating the electron beam to reduce the duty cycle. The condition here is that the modulation frequency must be high in comparison to ω/Q_L , the RF filling time for the accelerator structure. The minimum useable duty cycle is set by the length of the optical resonator for the oscillator which sets a lower limit to the pulse repetition frequency.

The minimum useable duty cycle for the superconducting accelerator operating at 1300 MHz is of the order of 1×10^{-2} . The corresponding power-limited peak current would be of the order of 10 Amps. The limit set by space charge effects was not known with precision but was estimated to be of the order of 1-10 A .

The general operating specifications for the pulsed gun system and the anticipated operating characteristics of the pulsed single pass oscillator have been described in the previous proposals and reports. Design work for the gun system was begun in this period. The objective of this effort was a reduction of the duty cycle by a factor of 110, e.g., the generation of an electron beam consisting of single electron bunches 4 psec in length separated by 85 nanoseconds.

A standard electron gun for the accelerator was modified by installation of a low inductance high perveance planar gridded cathode.[3] Given a pulse from the gun less than 1.5 nsec long, the pulse length will be reduced to 4 psec by the 1300 MHz chopper and buncher in the injector. The gun was designed to replace the cw gun customarily used in the injector. A single stage fast pulse amplifier and a 100 kV isolation transformer were also constructed to establish the feasibility of the electronics required to drive the gun.

Strong Signal Analysis: The quantum theory originally developed to analyze the operation of the free electron laser is formally limited to the small signal regime. Feynman's concept of the path integral provides

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an elegant and powerful means to analyze the strong signal problem. Calculations have been carried out to calculate explicitly the probability for the emission and absorption of an arb rary number of photons/electrons in the limit of small gain/pass (Figs. 3-7). Attempts are underway to extend the calculation to the large gain limit.

FIGURE CAPTIONS:

Figure 1: A schematic drawing of the single pass FEL oscillator.

Figure 2: A photo of the single pass oscillator showing the helium dewar for the helical magnet in the background and the CO_2 gain cell and resonator output mirror in the foreground.

Figures 3-6: These plots show the log of the probability for the radiation of an increment of energy in units of mc^2 by an electron whose initial energy is specified on the vertical axis, The figures show a contour plot of the log of the probability for four values of optical radiation power density. The optical power density is varied in steps of $\sqrt{10}$ from 178 (relative units) in the small signal regime to 5620 at saturation. The contour lines are spaced at intervals of 10^5 so that the probability is finite only near the maxima. As can be seen, the mean radiated energy is small when the optical power density is small while at large power density the radiated energy approached a constant value.

SINGLE PASS OSCILLATOR

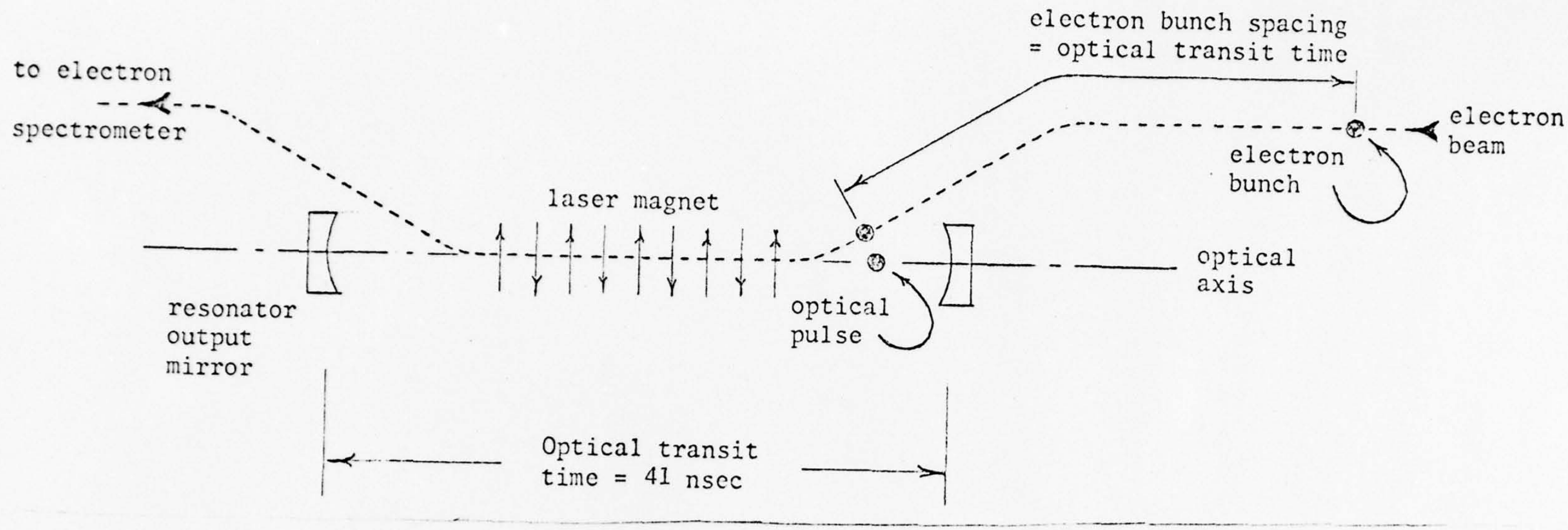

Figure 1

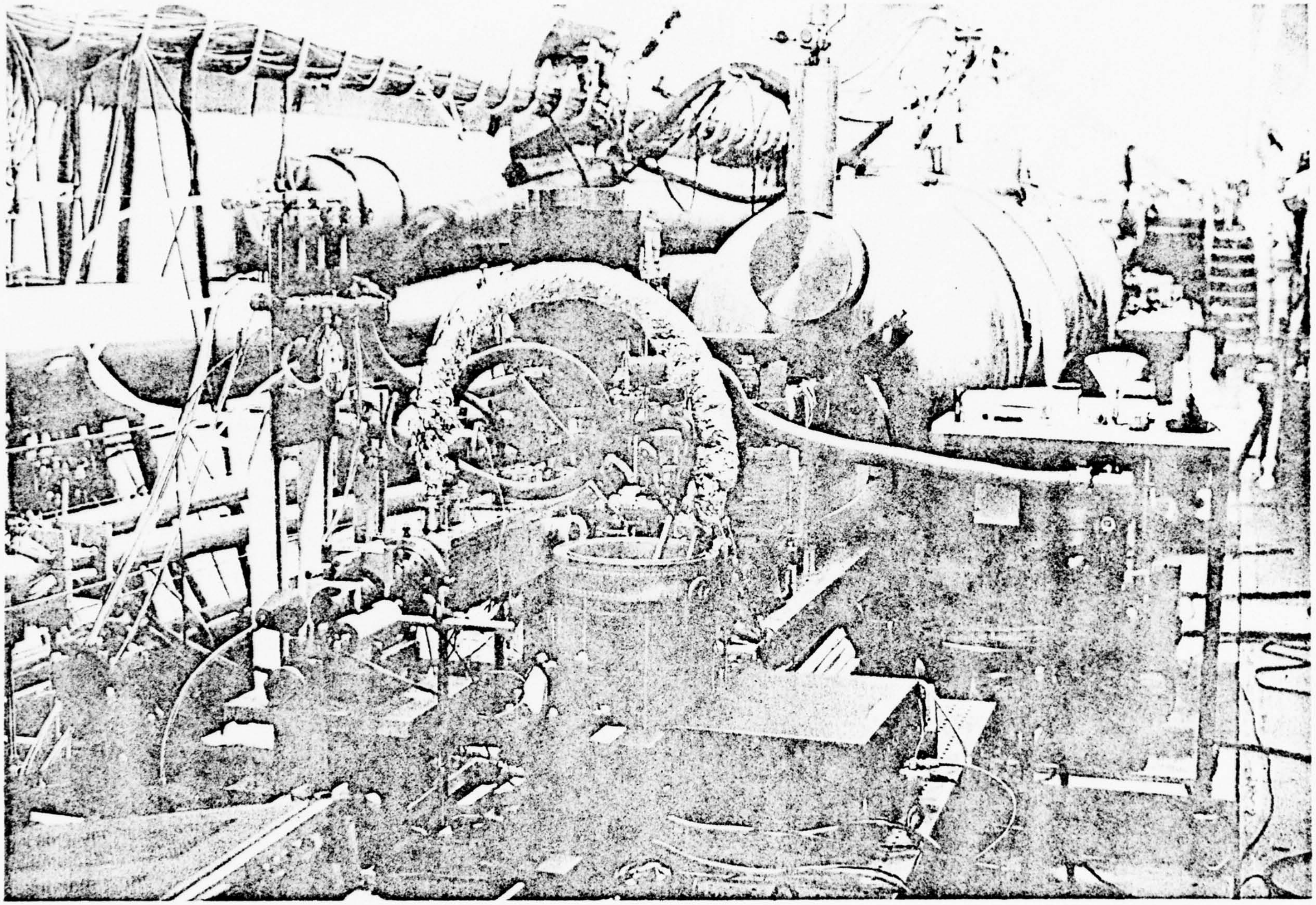

Figure 2

MAP ØF LØG10(AMP) FØR B0 EQUALS 178.
AL IS HØRIZONTAL, EP IS VERTICAL
CONTØUR STEPS ARE 1.E 05

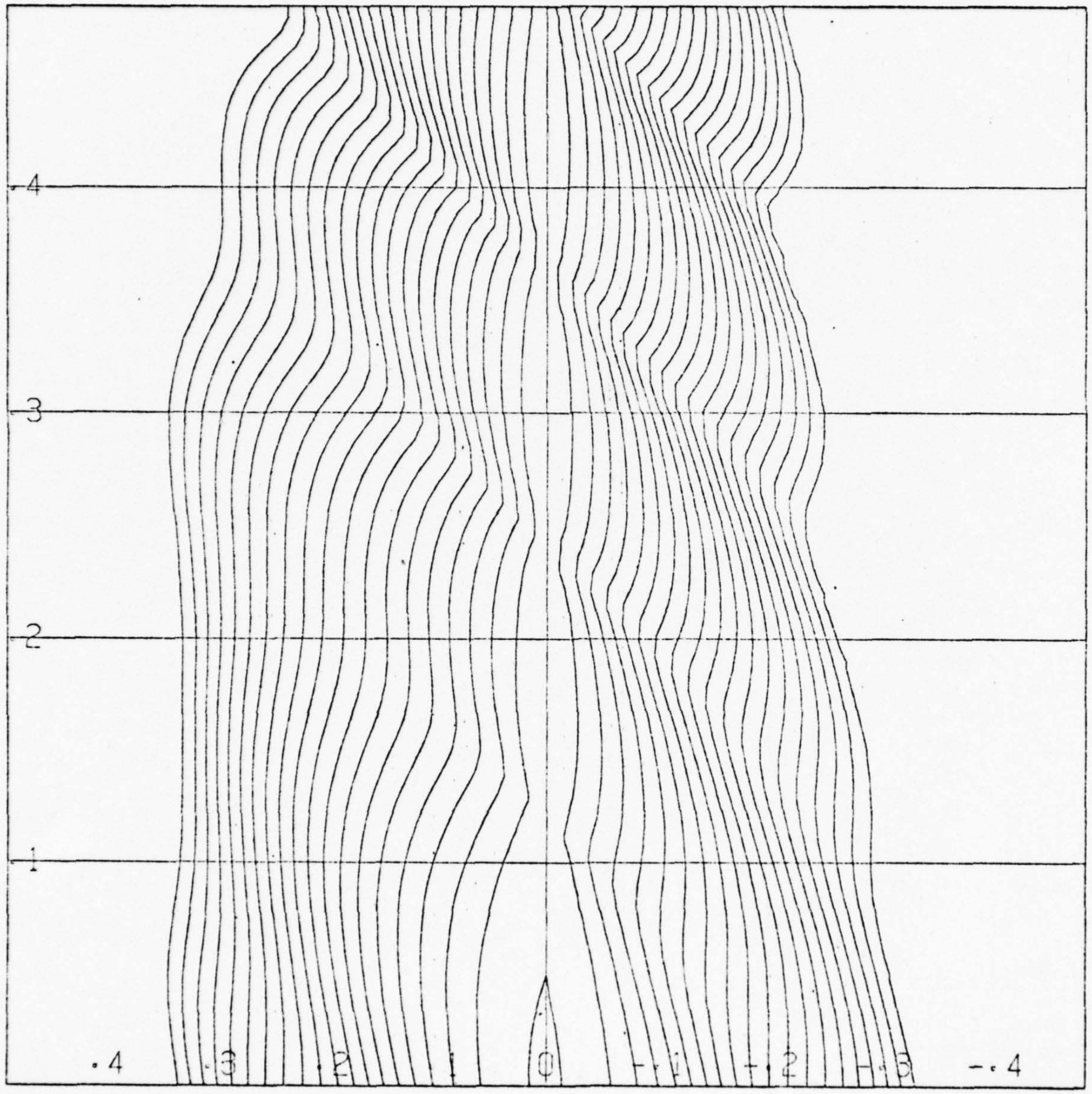

Figure 3

MAP OF LOG10(AMP) FOR BO EQUALS 562.
AL IS HORIZONTAL, EP IS VERTICAL
CONTOUR STEPS ARE 1.E 05

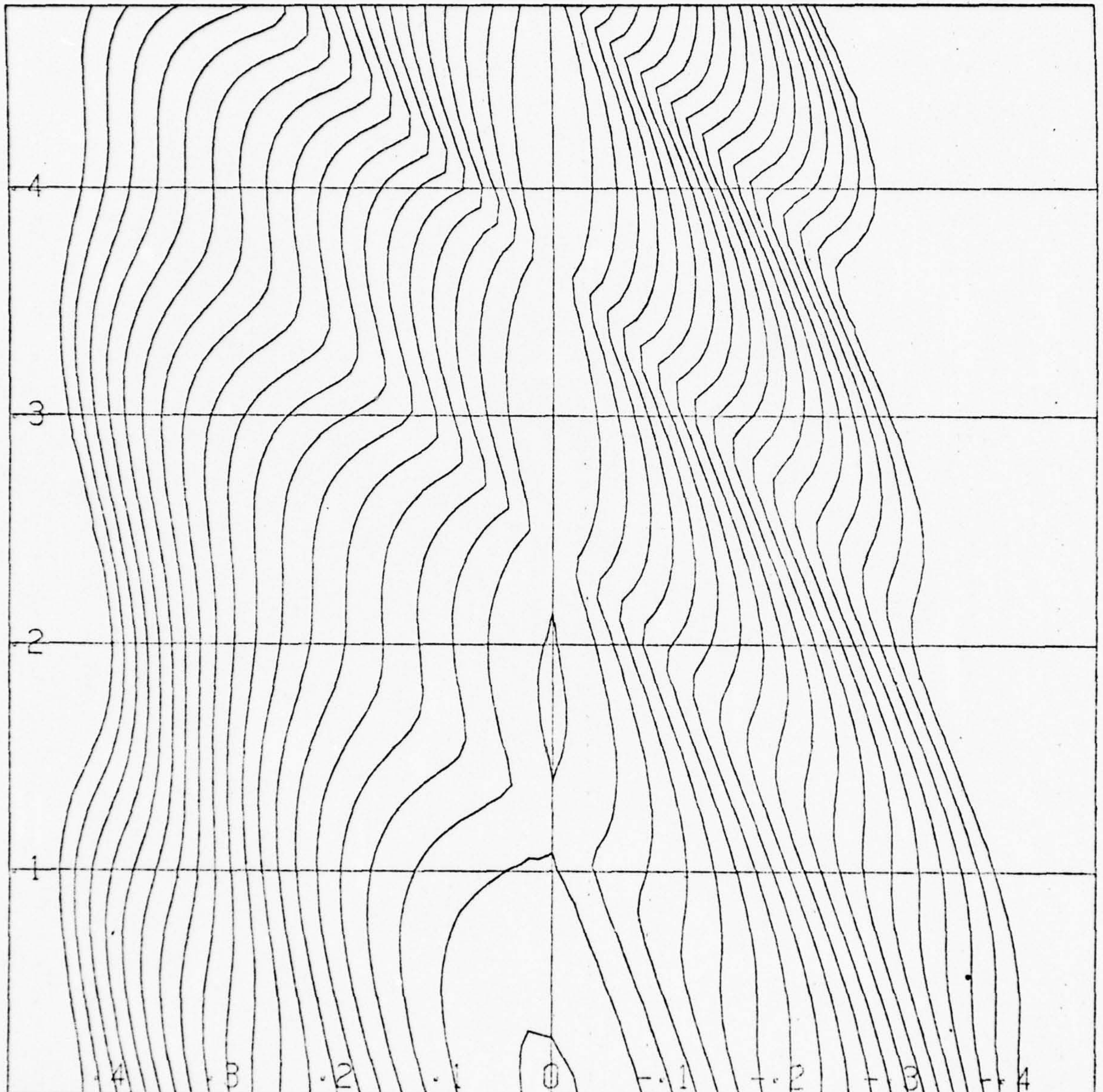

Figure 4

MAP ØF LØG10(AMP) FØR BO EQUALS 1780.
AL IS HØRIZØNTAL, EP IS VERTICAL
CØNTØUR STEPS ARE 1.E 05

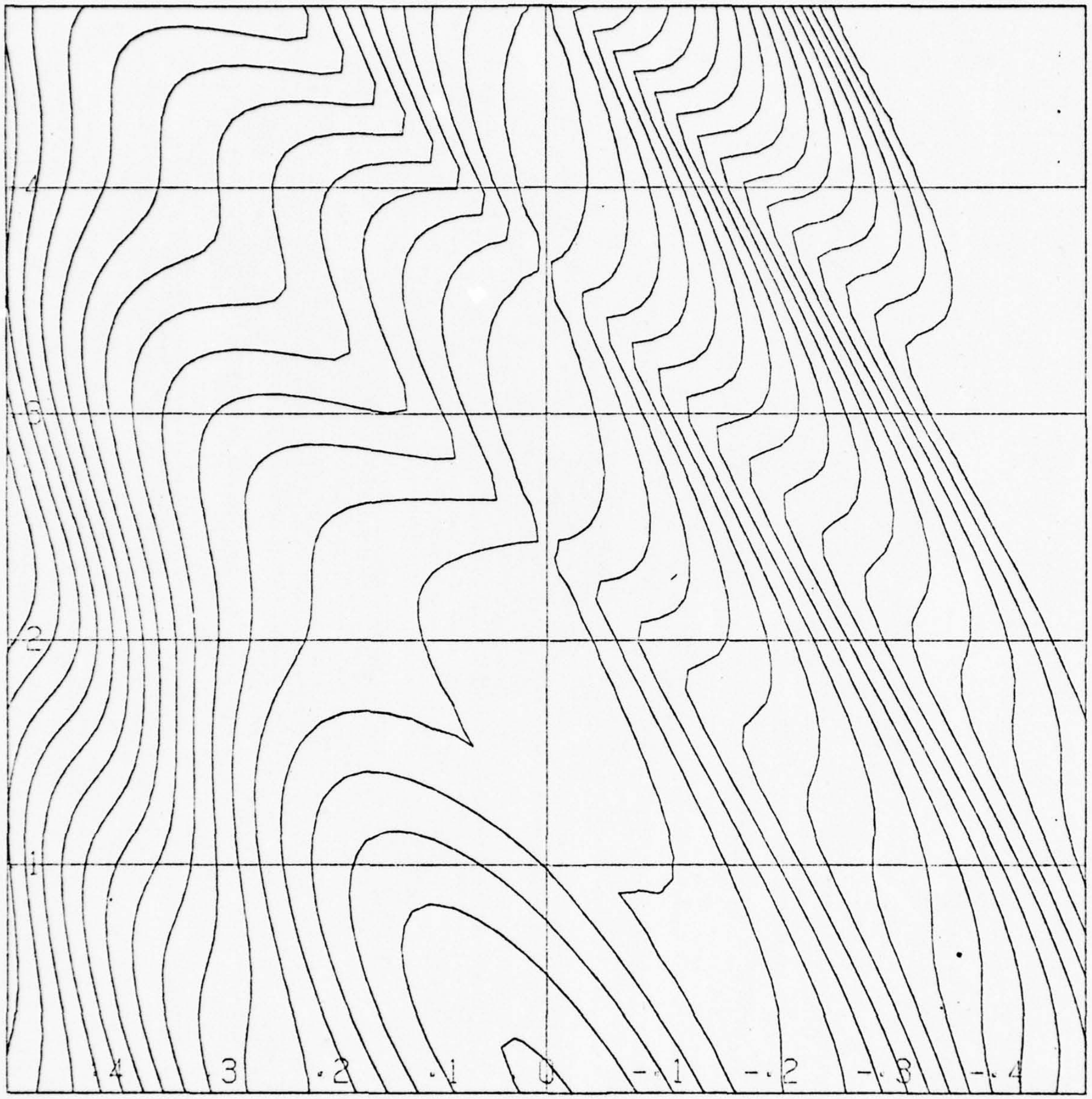

Figure 5

MAP OF LOG10(AMP) FOR BO EQUALS 5620.

AL IS HORIZONTAL, EP IS VERTICAL

CONTOUR STEPS ARE 1.E 05

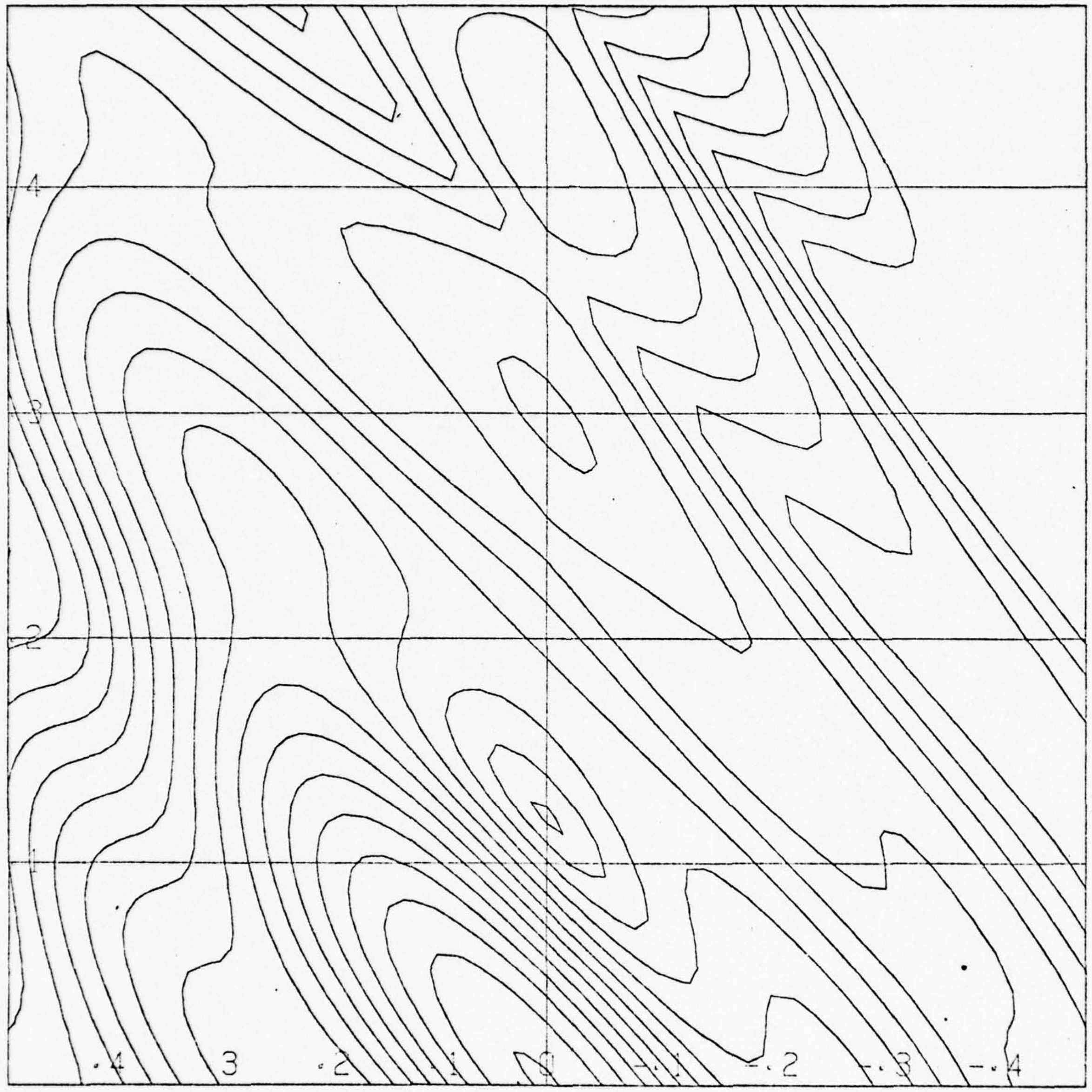

Figure 6

A DISCUSSION OF THE POTENTIAL OF THE FREE ELECTRON LASER AS A HIGH POWER TUNEABLE SOURCE OF INFRARED, VISIBLE AND ULTRAVIOLET RADIATION

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June 1976

I. INTRODUCTION

We have completed theoretical and experimental studies which establish the possibility of a new class of lasers based on the stimulated emission of radiation by a relativistic electron beam in a spatially periodic transverse magnetic field. Lasers based on this mechanism offer considerable promise as tuneable, high resolution, high power sources from the millimeter region to the ultraviolet. The characteristics of existing electron accelerators and storage rings suggest the possibility of an average power output in the range of 10^5 to 10^6 watts at high overall efficiency.

While the physics involved in the development of these devices is of interest in its own right, it is also clear that the realization of these capabilities could have a fundamental impact on areas of considerable technical significance including photochemistry, isotope separation and laser fusion.

II. BACKGROUND

An electron beam moving through a spatially periodic transverse magnetic field will amplify radiation moving with the beam through the field. The effect is illustrated schematically in Figure 1. If the electron energy is γmc^2, the magnet period is λ_q and the magnetic field is B, the wavelength for spontaneous radiation in the direction of motion of the electron beam is

$$\lambda \simeq \frac{\lambda_q}{2\gamma^2} \left(1 + \left(\frac{1}{2\pi}\right)^2 \frac{\lambda_q^2 r_o B^2}{mc^2}\right) \left(1 + \frac{h\nu}{\gamma mc^2}\right) \qquad (1)$$

(CGS units)

where λ and ν are the radiation wavelength and frequency, r_o is the classical electron radius and mc^2 is the electron mass-energy. This is also the wavelength for which stimulated emission is possible for radiation moving in the same direction.

Radiation can also be absorbed by the electrons. While the transition rate for absorption, integrated over all wavelengths, is essentially identical to the transition rate for stimulated emission, the two processes occur at slightly different wavelengths. The wavelength for absorption is

$$\lambda \approx \frac{\lambda_q}{2\gamma^2}\left\{1 + \left(\frac{1}{2\pi}\right)^2 \frac{\lambda_q^2 r_o B^2}{mc^2}\right\}\left\{1 - \frac{h\nu}{\gamma mc^2}\right\} \qquad (2)$$

which is shorter by the fraction $(2h\nu/\gamma mc^2)$ than the wavelength for stimulated emission.

For any practical case at optical wavelengths, the lineshapes for emission and absorption will overlap and the net available gain - proportional to the difference between emission and absorption - will have a wavelength dependence proportional to the derivative of the lineshape for spontaneous emission. The relationship is illustrated schematically in Figure 2; an experimental comparison appears in Figure 3.

The amplification mechanism transforms electron kinetic energy directly to radiation. The unique feature of the mechanism is the capability to select the operating wavelength through adjustment of the electron beam energy and the magnetic field. For a magnet period of one centimeter and a 10 MeV electron beam the wavelength would be 12 μ at low magnetic field;

at 100 MeV the wavelength would drop to 1200 Å. The available gain drops at short wavelengths but the wavelength range for which useful gain would be available with existing electrons sources appears to extend to below 1000 Å.

Radiation emitted by electrons within a magnetic field is properly termed magnetic bremsstrahlung while absorption occurs via inverse bremsstrahlung. The stimulated emission of magnetic bremsstrahlung in a periodic field was first analyzed by Madey et al.[1] The idea can be traced back to Motz et al,[2] who proposed the use of a periodic magnetic field - a "wiggler" magnet in contemporary parlance - as a narrow-band spontaneous emission source. The stimulated bremsstrahlung problem is closely related to the problem of stimulated inverse Compton scattering, analyses[3] of the latter having been performed by Dreicer,[4] Pantell et al[5], Sukhatme and Wolff,[6] and Kroll.[7] Finally, a numerical analysis of the energy lost to radiation by a relativistic electron beam in a periodic magnetic field has been performed by Lin and Dawson[8] who found the system capable of large power output. Other free electron amplifiers have also been developed including the cyclotron maser[9] and a device based on the magneto-raman effect,[10] however, the physics and characteristics of these amplification mechanisms are distinct and these devices appear limited to the longer wavelengths.

III. PRESENT STATUS

In the experiments we have completed, a 24 MeV electron beam was used to amplify the 10.6 μ radiation from a TEA CO_2 laser. The periodic field was generated by a bifilar helical winding 5.2 meters in length with a 3.2 cm period. The magnitude of the magnetic field on axis was constant; the field vector rotated in the plane normal to the axis with the period of the winding. The electron beam and the 10.6 μ radiation were sent through an evacuated copper tube on the axis within the winding. The experiment is described in Phys. Rev. Letts. 36 p. 717 (1976) ~~HEPL Report No. 759 (enclosed)~~ and the set-up is shown schematically in Figure 4.

Measurements were made of the magnitude of the gain, the lineshape and the power radiated by the electron beam. A gain of 7% per pass was obtained at a magnetic field of 2.4 kgauss and an electron current of 70 mA. The linewidth for amplification was homogeneously broadened, e.g., the observed linewidth was close to the limiting value set by the finite length of the interaction region. Finally, a lower bound to the radiated power for saturation was obtained; the magnitude of the gain and the lineshape were unchanged during experiments in which the electrons radiated 0.25% of their energy in passage through the interaction region.

The measured gain and the dependence on electron current, energy, magnetic field and polarization are in reasonable agreement with the theory. Given the measurement at 10 μ , the theory can be used to estimate the gain available at shorter and longer wavelengths and the electron current required for operation.

The attainment of the homogeneously broadened linewidth is significant since it establishes that it is possible to generate an electron beam in which all the electrons couple to the radiation field. This is an important consideration in determining the saturated power output and the fluctuations in the energy radiated by the electrons in the interaction region.

Finally, the establishment of a lower bound to the radiated power for saturation is important because it establishes the potential for the high power output. Conservation of energy requires that the gain in energy by the radiation field in the interaction region be balanced by the loss in energy of the electrons. Saturation occurs when the change in electron energy moves the wavelength for radiation outside the lineshape for spontaneous emission, e.g., when the fractional energy loss approaches the fractional linewidth. For homogeneous broadening, the fractional linewidth is a constant determined by the magnet length and period, and the energy loss per electron is uniform except for statistical fluctuations. Given a lower bound for the saturated power output at 10 μ , the saturated power output scales as the product of the electron beam current and voltage.

IV. SCALING

The experiments and the theory provide a basis for specifying the electron beam parameters required for device operation and also for estimating the device characteristics. We consider here a laser oscillator.

The gain per pass required for oscillator operation depends on the resonator losses; a per pass gain of 3dB would appear adequate barring any unusual circumstances. The electron current required for operation is then a function of wavelength and the size of the resonator mode to which the electron beam is coupled. The small signal theory yields for the gain per centimeter

$$G = \frac{1}{2\pi} \frac{1}{\sqrt{e\pi}} \frac{r_o^2 \rho_e B^2 \lambda_q^{3/2} \lambda_f^{3/2}}{mc^2 (\Delta\nu/\nu)^2} \times \text{(filling factor)} \qquad (3)$$

(CGS Units)

where $e = 2.72$, ρ is the electron density, λ the wavelength, and $(\Delta\nu/\nu)$ the $(1/e)$ halfwidth of the lineshape for spontaneous emission. The fractional linewidth $(\Delta\nu/\nu)$ is equal approximately to $(\lambda_q/2\ L)$ for a magnet of length L. The filling factor is the ratio of the cross section of the electron beam to the resonator mode.

The gain was calculated using the Weizsacker-Williams approximation exploiting the Compton Scattering analogy. Note, however, that the functional dependence on electron density, magnetic field, and wave length is dictated by Lorentz invariance, symmetry and dimensionality and is model-independent.

The scaling of gain with wavelength is influenced by the coupling of the electron beam to the field. The gain equation was derived for the case of a plane wave final state and an infinite, homogeneous electron beam. The plane wave assumption is justified by the observation that the local field in an overmoded resonator is indistinguishable from a plane wave, however, a correction must be introduced for the finite size of the electron beam. The matrix element for radiation into one of the normal modes of the field in the resonator will be proportional to the average over the electron's trajectory of the amplitude of the spatial part of the quantized vector potential for the mode. The transition rate, averaged over all the electrons in the beam, will be proportional to the convolution of the electron density distribution function and the square of the normalized spatial part of the potential. The convolution integral yields the filling factor which, for a small electron beam, is equal to the ratio of the cross section of the electron beam to the area of the mode. The mode area can be defined as the ratio of the power propagating in the mode to the power density on axis. The filling factor is unity if the e-beam cross section exceeds the mode area.

In a waveguide, the mode area is independent of wavelength and the gain scales as $\lambda^{3/2}$. This was the situation in the 10 μ experiments we have performed and we have plotted, in Figure 5a, the expected wavelength dependence together with the measured value at 10 μ.

In an optical resonator, the mode area is determined by diffraction and therefore involves the wavelength as well as the mirror spacing and curvature. For optimum coupling, e.g., minimum mode area, the mode area can be shown to equal $(\lambda L/3)$ where L is the interaction length. The gain therefore scales as $\lambda^{1/2}$ down to the wavelength at which the electron beam fills the mode and a $\lambda^{3/2}$ dependence resumes. This case is illustrated in Figure 5b. Note that the mode size should not be reduced below the electron beam radius; there would be no benefit in terms of the available gain and the electrons outside the mode would be decoupled from the field leading to non-statistical variations in the electrons' energy loss in the interaction region.

The plotted curves in Figure 5 indicate the calculated gain per pass at one ampère for a 1 mm^2 e-beam cross section. As previously noted, the scaling of gain with wavelength, current and magnetic field is model independent. The curves in Fig. 5 are therefore guaranteed correct to within a constant factor.

For a gain of 3dB/pass and optimum coupling an electron current of 0.3 A is required at 10 μ and 15A at 1200 Å assuming a 1 mm^2 e-beam and the conditions in the 10 μ experiment. The corresponding e-beam energies are 24 MeV at 10 μ and 220 MeV at 1200 Å. These figures, while obviously specific to the magnet design, are typical of the requirements for the operation of a device.

The possibilities for operation at high power are readily apparent. We know from the experiment that 0.25% of the electrons energy can be converted to radiation within the interaction region without saturating the amplification mechanism. For a 15 A (peak) electron beam at 220 MeV this corresponds to a peak power output of 8×10^6 watts. The experimental lower bound is close to the value estimated from theory for a constant period helix. An energy conversion of 10% appears possible if the helix period were varied to compensate for the decay in electron energy along the length of the interaction region.

While the saturation characteristics are obviously attractive, it should be noted that practical problems not directly related to the amplification mechanism are likely to require careful attention for high power operation. The optics problem for a high power resonator will be difficult. Optimum coupling corresponds to minimum mode size in the interaction region and large power density at the mirrors. The power density close to the interaction region for operation in the megawatt range could exceed 10^8 watts/cm^2 and it is likely that special optics will have to be developed to handle the problem. One approach we have considered is the use of a water-cooled grazing incidence reflecting beam expander. The scheme is attractive because it takes advantage both of the reduction in the power density at the mirror surface and the improvement in the reflectivity at small angles of coincidence. Some work has been done in industry on the development of such systems.[11]

The physics of the amplification mechanism leads to a number of independent constraints on the electron beam homogeneity, radius, and angular divergence. The constraints can be derived from the condition that the electrons in the beam should couple to the electromagnetic field in an identical manner. This is the condition for maximum gain and power output and minimum variation in the electrons energy loss in the interaction region. Given identical coupling, the bandwidth for amplification will be homogeneously broadened, e.g., the bandwidth will be inversely proportional to the interaction time.

The wavelength for radiation is a function of the electron energy, the magnetic field, and the direction of the electron's motion. Neglecting the quantum correction,

$$\lambda \approx \frac{\lambda_q}{2\gamma^2}\left[1 + \left(\frac{1}{2\pi}\right)^2 \left(\frac{\lambda_q^{\,2}\, r_o\, B^2}{mc^2}\right) + \gamma^2\theta^2\right] \qquad (5)$$

Here θ is the angle between the direction of the electron's motion and the direction of the radiation. Maxwell's equations require the amplitude of a static magnetic field, periodic in z, to vary with radius; for a helically symmetric field, as was used in the experiment, the field has a minimum on axis and increases as the square of the displacement off axis. In the wavelength equation, B, and therefore λ, are thus functions of the radial displacement of the electron's trajectory from the axis of symmetry.

The condition for homogeneous coupling is that the variation in wavelength due to the electron's spread in energy ($\Delta\gamma$), radius ($\Delta\rho$), and angle ($\Delta\theta$) be small in comparison to the linewidth for spontaneous emission, the latter being approximately equal to $(1/n)$ where n is the number of magnet periods:

$$\frac{1}{\lambda}\,\frac{\partial\lambda}{\partial\gamma}\cdot\Delta\gamma < \frac{1}{n}$$

$$\frac{1}{2\lambda}\left(\frac{\partial^2\lambda}{\partial\rho^2}\right)\cdot(\Delta\rho)^2 < \frac{1}{n} \qquad (6)$$

$$\frac{1}{2\lambda}\left(\frac{\partial^2\lambda}{\partial\theta^2}\right)\cdot(\Delta\theta)^2 < \frac{1}{n}$$

For the magnet in the experiment these equations imply an upper limit for $(\Delta\gamma/\gamma)$ of 3×10^{-3} ; for $\Delta\rho$, 0.8 mm; and for $\Delta\theta$, 10^{-2} radians at 10μ and 10^{-3} radians at 1200 Å. While the numbers are obviously specific to the magnet design, they are indicative of the quality of the electron beam required.

V. ELECTRON STORAGE RINGS

Electron storage rings were developed approximately fifteen years ago as a research tool for high energy physics. Large circulating currents have been obtained in storage rings and the homogeneity and emittance of the beam are well suited to electron laser requirements. The circulating beam current can be exploited for laser applications by inserting a periodic array in a straight section of the ring. Storage rings appear to provide the means for operation at high overall efficiency and high average power with a tuning range of several octaves. Sufficient current has been obtained in existing storage rings for operation at wavelengths to 1200 Å.

The performance of the Princeton-Stanford ring illustrates the capability of these machines. This ring was one of the first to be built and was designed for operation at a maximum energy of 500 MeV. A picture of the ring is shown in Figure 6.[12] The characteristics of the ring[13] at 300 MeV are tabulated below.

instantaneous peak current (maximum observed)	=	15 A
corresponding avg. current	=	0.4 A
homogeneity $(\Delta\gamma/\gamma)$	≈	2×10^{-4}
beam emittance	≈	0.2 mm-mrad

These numbers can be compared with the requirements for laser operation (Sec. IV). The peak current and homogeneity are substantially better than required and the beam emittance is within the allowable upper limit to the product of the beam radius and divergence. Higher currents by an order of magnitude have been reported in the literature at this energy, however, the citation[14] does not include specification of the homogeneity and emittance. A contemporary machine, the SPEAR ring at SLAC, has delivered a 100 amp instantaneous peak current at an energy of 1.5 GeV.[15]

A storage ring consists of a set of bending and focussing magnets to guide the circulating electrons around in a closed stable orbit. The electron beam is injected from an accelerator using a pulsed inflector magnet to kick the injected beam into the ring. Injection is usually continued over a number of orbits. The ring integrates the current from the accelerator and the current in the ring can exceed the accelerator current by a substantial margin. The accelerator used for injection is turned off after the ring is filled.

The beam lifetime in a well-designed ring is limited by scattering from the background gas. At very high current additional losses occur due to electron-electron scattering in the circulating beam (the Touschek effect).[16] The vacuum requirements for storage rings are stringent: a vacuum of 10^{-9} torr was required to attain a 20 hour beam lifetime in the Princeton-Stanford ring. The beam lifetime at high current is inversely proportional to the charge density.

In conventional rings, electrons lose energy continuously via synchrotron radiation in the bending magnets and this energy must be replaced to maintain the equilibrium. This is accomplished by means of a radio-frequency or microwave cavity within the ring driven at a frequency equal to an integral multiple of the orbit frequency. Given an adequate voltage gradient in the cavity, there will always be a phase at which an electron circulating in the ring will gain sufficient energy from the field to balance the losses due to radiation. The circulating beam will then have the form of one or more bunches, depending on the harmonic number, positioned at the phase-stable points. The bunch length will be determined by the equilibrium energy spread and the strength and frequency of the accelerating field. The ratio of bunch length to bunch spacing is typically of the order of 10%.[17]

After the ring is filled, the energy of the circulating beam can be varied by changing the magnetic field in the bending and focussing magnets. The storage ring is basically an electron synchrotron in which the beam is never extracted; the machine can be used to accelerate or decelerate the circulating beam within the overall limits imposed by magnet design and beam dynamics. In the Tantalus I machine at Wisconsin, the ring is filled at 40 MeV and accelerated internally to 240 MeV for operation.[18]

The characteristics of the circulating electron beam at equilibrium are determined by the competition between the statistical fluctuations in the electrons' radiative energy loss and the damping arising from the strong energy dependence of this loss.[19] As evidenced in the characteristics of the Stanford-Princeton ring, the overall effect is to produce at equilibrium a well-collimated highly homogeneous circulating beam.

A schematic of an electron storage ring-free electron laser is shown in Figure 7. For an oscillator, the mirrors for the resonator can be placed outside the electron beam orbit, leaving an aperture in the side of the bending magnet to admit the radiation.

The electrons in the ring would circulate alternately between the interaction region in the periodic magnetic field and the accelerating cavity. The electrons can be thought of as converting the RF energy in the cavity to optical energy in the periodic field. Electrons moving through the periodic field will amplify the radiation in the resonator. Having lost a fraction of their energy to the radiation field, the electrons will be re-accelerated to the original energy in the RF cavity and proceed to move again through the interaction region. The process will proceed at equilibrium for a length of time limited only by the lifetime of the circulating electron beam.

The electrons in the ring are bunched by the accelerating field in the rf cavity and electrons moving through the periodic field will amplify only that radiation which spatially overlaps the bunch. The radiation field in the cavity will therefore be time dependent consisting of pulses equal in length to the bunch length and with a separation related to the bunch spacing. It will be necessary to adjust the mirror spacing so that the radiation pulses propagating within the resonator will overlap with the circulating electron bunches in the interaction region; the radiation pulse spacing will then be an integral sub-multiple of the electron bunch spacing. In the Princeton-Stanford ring the bunch length was 2 nanoseconds with a separation of 40 nanoseconds.

The appeal of this concept lies in the prospect of tuneable operation at high power and high efficiency. The wavelength of operation is a function both of the electron energy and the magnetic field and both of these quantities can be varied in a continuous manner. An operating range in energy of 2:1 seems well established for storage rings: the corresponding range in operating wavelength would span 2 octaves. Given that electron beam quality can be maintained there is the prospect for operation at high resolution and high power throughout this range.

The prospect for high power operation was discussed on page (8) and stems from the observation that it has been possible to convert 0.25% of the electrons energy to radiation in the interaction region without evidence of saturation. For the 0.4 A average current, in the Princeton-Stanford ring, this would correspond to an average power output of 2×10^5 watts at a wavelength of 1200 Å (beam energy = 220 MeV).

The prospect for high efficiency stems from the use of the electron beam as a "working fluid" transporting energy from the rf field in the accelerator cavity to the optical radiation field in the interaction region.

There are no intermediate steps between acceleration of the electron beam and radiation in the periodic magnetic field. While incoherent synchrotron radiation will occur as a parasitic process in the bending magnets for the ring, the power lost would be small by comparison, amounting to a few hundred watts for the Princeton-Stanford ring at 200 MeV and 0.4 A. The overall efficiency will then be determined by the efficiency of the RF generator for the accelerator cavity, by cavity losses, by copper losses in the magnets for the ring, and by the operating and standby power of the accelerator used for injection. The latter figure is the most difficult to estimate. With respect to the ring itself, estimates for the overall efficiency range in excess of 20% for power outputs greater than 10^5 watts. The accelerator injector operating power presumably becomes small if a reasonable stored beam lifetime can be realized.

The major questions concerning the realization of such a device relate to the perturbation of the electron dynamics by the periodic magnet array and the radiation field. The perturbations can be divided into two classes: (1) those relating to the operation of the ring when "cold", e.g., when radiation losses in the interaction region are small, and, (2) the perturbations associated with the statistical fluctuations in the radiated energy when the radiated power is large.

Considerations of the first sort will affect the design of the electron optics and the decision as to the type and placement of the focussing magnets to achieve a beam of the required cross section and divergence within the interaction region. We note, in this regard, that the beam diameter must be held to a small value over an extended length. While the periodic field is itself a focussing system, it may be necessary to include additional focussing elements distributed along the interaction region to confine the beam. Also, a helical field will couple the horizontal and vertical betatron oscillations and the effects on beam size and stability will have to be carefully explored. But this portion of the problem involves nothing fundamentally new and can be analyzed within the framework of the existing theory using existing computer codes.

The part of the problem relating to the statistical fluctuations in energy loss is more complicated. The equilibrium energy spread and beam emittance in a storage ring are determined by the competition between the quantum fluctuations in radiation and the damping derived from the energy dependence of the radiated power. The electron beam characteristics are therefore sensitive to the modification of these phenomena. The feasibility of the laser concept requires that the two mechanisms remain in balance over the full range of radiated power output.

At high radiated power, one expects that the statistical fluctuations will be larger than in a conventional ring because of the larger number of photons. But the coupling to the radiation field in the periodic magnet is also strongly dependent on energy (Figs. 2 and 3) so there will be strong energy dependent damping. Note that the Robinson theorem[20] does not apply in this case since the theorem was derived for the case of spontaneous synchrotron radiation. The dominance of stimulated emission in the periodic field changes the rules for radiation and leads to an enhanced damping rate.

The energy spread can be estimated from the theory. It is found that the effect of statistical fluctuations is small in comparison to the damping arising from the energy dependence of the amplitude for emission.[21] The combination of strong damping and small fluctuations indicate that the electrons beam will not be degraded as a consequence of laser operation. But, as opposed to the question of the "cold" electron optics, the physics for this problem is new and confirmation of the theory and the capability for high power operation requires performance of the experiment.

VI. OTHER ELECTRON SOURCES

Two other sources have the demonstrated capability to generate an electron beam for use with this class of laser. The superconducting linear accelerator (SCA) in the W. W. Hansen High Energy Physics Laboratory produces an exceedingly high homogeneity and low emittance electron beam. The beam quality led to the choice of the SCA as the e-beam source for the 10 μ experiments. The peak current presently available from the SCA is however, marginal for oscillator operation.

The average current output of the SCA is limited by the available klystron power. Higher peak current can therefore be obtained at the expense of the duty cycle. The electron beam from the SCA consists of bunches 4 psec in length separated by 769 psec. The instantaneous peak current is limited to 70 mA. We have proposed to fit a modulator to the cathode of the 100 kv gun for the accelerator to reduce the duty cycle by a factor of 130, e.g., to maintain the bunch length while increasing the bunch spacing to 100 nsec. Given the same average current, a peak current in excess of 1A should be possible with this system.

An oscillator has been constructed using this beam and the magnet from the 10 μ experiments (Figure 8). Magnets are used to deflect the e-beam onto the optical axis so as to bypass the resonator mirrors. Electrons emerging from the interaction region are transported to a spectrometer and beam dump in the end station. As in the case of the storage ring, the mirror spacing must be adjusted to match the bunch spacing. Optical radiation within the resonator will consist of pulses equal in length to the electron bunches and separated by the bunch spacing.

With respect to the device physics, the SCA oscillator experiment is of interest for the information it will provide on operation at saturation, particularly, the relationship of gain to optical power density and the statistical fluctuations in the electrons' energy loss in the interaction region. For the latter measurement, the electron beam will be run from the oscillator to a high dispersion magnetic spectrometer for analysis. The measurement will provide an important check on the fluctuation theory for the storage ring problem.

Technical interest in the SCA oscillator arises from its potential as a tuneable picosecond optical source of relatively high peak and average power. The oscillator has been designed for operation at 10 μ but, given a 1 A peak current, it has the potential for operation throughout the infrared and visible regions.

It is also possible to generate high quality electron beams using a megavolt electrostatic generator. The problem here is the limited current available from the high voltage terminal. The problem can be solved by using the generator simply to bias the cathode with an independent low-voltage power supply to collect the electrons passing through the interaction region and return them to the cathode.[21] The concept is the "hard-wired" analog of the high energy electron storage ring. The idea is promising at electron energies of up to a few MeV, e.g., in the millimeter and sub-millimeter regions.

VII. SHORT PULSE OPERATION

The characteristics of an electron laser device will be determined by the characteristics of the electron beam. High average power e-beams are available, thus, there is a potential for high average power output. Tuneable high average power lasers are required to do large scale photochemistry. High energy pulsed lasers are also required, for example, in the laser fusion program.

There are several means by which a free electron laser could be adapted to generate short high energy pulses. A high power free electron laser oscillator could be used to optically pump the upper level in a conventional atomic or molecular laser. The energy deposited in the upper level would be stored for a period of time equal to the level lifetime. The optically pumped system could then be used as the final amplifier with a low power optical master oscillator to generate high energy pulses at arbitrary shape and duration.

The utility of this scheme depends on the availability of a suitable high average power pump and the lifetime of the excited level. The electron laser offers promise as a tuneable narrow-band source with an average power output in excess of 10^5 watts. We note also that the requirement of a long excited level lifetime is independently imposed on high energy lasers to reduce the gain per unit length to manageable proportions. Species considered for high energy system have metastable excited level lifetimes ranging from 10 milliseconds to 1 second.[22] Given a 10^5 watt average power optical pump and a 1 second lifetime there is the possibility of 10^5 joules stored energy in the medium. Optical pumping is an effective means to generate level inversion in large volume systems and there is the possibility that the use of optical pumping will permit the exploitation of an atomic or molecular species with more favorable characteristics than the present candidates for high energy laser development.

A second possibility would be to operate an electron beam laser directly as a short pulse source. High energy optical pulses could be developed within the resonator of a storage ring electron laser oscillator if the resonator mirrors were made completely reflecting. Starting from the power radiated spontaneously by the electron beam, the optical pulse energy would grow in time to a limiting value determined by the mirror absorption and the electron laser saturation characteristics. At the appropriate time the optical pulse would be deflected by a small angle and extracted from the cavity.[23]

To estimate the order of magnitude of the attainable optical pulse energy, we will assume that 100 joules can be stored as kinetic energy in a single electron bunch. We note that this bunch energy has already been attained in the SPEAR storage ring at SLAC. The saturation characteristics of the amplification mechanism are such that 1% of this energy, or 1 joule, ought to be extractable as optical radiation on each pass through the resonator with the appropriate magnet design. If the absorption coefficient of the resonator mirrors can be maintained below 1×10^{-3} the equilibrium optical pulse energy would exceed 10^3 joules.

The optical pulse shape would be determined by the charge distribution in the electron bunch. In a storage ring, considerable control can be exercised over the distribution by choice of the operating frequency and harmonic content of the rf accelerating field. The potential for operation at high efficiency and high repetition rate and the use of free electrons in high vacuum as the amplifying medium lends considerable appeal to this concept. Note, however, that the concept requires the development of a high speed optical element to deflect the high energy optical pulse out of the resonator.

VIII. SUMMARY

Theory predicts that a relativistic electron beam moving through a spatially periodic transverse magnetic field can be used to amplify electromagnetic radiation. According to theory, the electron beam can be thought of as a new type of active medium for the construction of a new class of laser amplifiers and oscillators. The effect is interesting because of the possibility for continuously tuneable operation over a broad range of wavelengths, from the millimeter region to the ultraviolet.

The effect has been observed in experiments performed at $10\ \mu$. A 24 MeV electron beam was used to amplify the coherent radiation from a $10.6\ \mu$ CO_2 TEA laser. The gain is close to the expected value and the experiments establish the capability for high power output.

The mechanism requires a high energy, high current, high quality electron beam and the question of technical feasibility revolves around the capability to generate such beams. Several approaches can be used but the most promising involves the use of an electron storage ring. A ring can be used to integrate the output of a low current accelerator over a period of time and synchrotron radiation compresses the circulating electrons into a compact region of phase space. Electron beams sufficient for laser operation at wavelengths to 1200 Å have been available in storage rings for ten years.

The idea is to construct the ring in the form of a racetrack including the periodic magnet array in one of the straight sections. The configuration holds great promise as a tuneable high power source capable of operation at high overall efficiency.

A fundamental question is the effect of high power operation on the distribution function for the circulating electrons. The distribution reflects the relative roles of the statistical fluctuations and damping due to radiation. Theoretical estimates indicate that energy flucutations will be small due to the dominance of damping effects. Experiments are now being prepared to check the fluctuation theory.

The development of a narrow-band, tuneable, high average power source is obviously relevant to photochemistry and isotope separation. Operated as an optical pump, the device could also make possible an important means for the production of short high energy optical pulses for pellet compression and other applications.

IX. REFERENCES

1. J.M.J. Madey, J. Appl. Phys. 42, 1706 (1971), also J.M.J. Madey, H. A. Schwettman and W.M. Fairbank, IEEE Trans. Nucl. Science, NS-20, 980 (1973).

2. H. Motz, J. Appl. Phys. 22, 527 (1951); H. Motz, W. Thon and R.N. Whitehurst, J. Appl. Phys. 24, 826 (1953); H. Motz and M. Nakamura, Ann. Phys. (NY) 7, 84 (1959); H. Motz and M. Nakamura, Proc. of the Symposium on Millimeter Waves, Microwave Research Institute Symposium Series, Vol. IX (New York: Interscience, 1960) p. 155.

3. While the published Compton scattering gain formula can be reduced to a common functional form, the numerical factors are such that the predicted gains differ up to two orders of magnitude.

4. H. Dreicer, Phys.Fluids, 7, 735 (1964).

5. R. H. Pantell, G. Soncini and H. E. Puthoff, IEEE J. Quantum Elect. 4, 95 (1968).

6. V.P. Sukhatme and P.A. Wolff, J. Appl. Phys. 44, 2331 (1973).

7. N. Kroll, in Stanford Research Institute Technical Report No. JSR-74-1, 1975 (unpublished), p. 74.

8. A. T. Lin, J. M. Dawson and H. Okuda, Phys. Fluids, 17, 1995 (1975).

9. J.L. Hirshfield, I.B. Bernstein and J.M. Wachtel, IEEE J. Quantum Elect. 1, 237 (1965).

10. V.L. Granatstein, M. Herndon, R.K. Parker and S.P. Schlesinger, IEEE Trans. Microwave Theory and Tech. MTT-22, 1000 (1974).

11. H.P. Brueggemann, Conic Mirrors, The Focal Press: London (1968), p. 107.

    Spawr Optical Research, Inc.; personal communication.

12. The photo appeared in "Particle Storage Rings" by G.K. O'Neill, Scientific American (November, 1966) p. 107.

13. W. C. Barber, Hansen High Energy Physics Laboratory Internal Report No. HEPL-374 (unpublished) 1964.

14. A.N. Skrinsky, IEEE Trans. Nucl. Sci. 3, 756 (1966).

15. H. Winick, Stanford Linear Accelerator Center Publication No. 1439 (1974).

16. C. Bernardini, G.F. Corazza, G. DiGiugno, G. Ghigo, J. Harnski, P. Marin, R. Querzoli and B. Touschek, Phys. Rev. Letters 10, 407 (1963).

17. M. Sands, The Physics of Electron Storage Rings: An Introduction; Proceedings of the Scuola Internazionale di Fisica "E. Fermi," Varenna: 1969) p. 257.

18. E. M. Rowe, IEEE Trans. Nucl. Sci., NS-20, 973 (1973).

19. M. Sands, op. cit.

20. K.W. Robinson, Phys. Rev. 111, 373 (1958).

21. D. Deacon and J.M.J. Madey (unpublished).

22. Stanford Research Institute Technical Report No. JSR-74-1, 1975, (unpublished) p. 18.

X. FIGURE CAPTIONS

Fig. 1: Configuration of Periodic Magnetic Field, Electron Beam and Radiation.

Fig. 2:
a. Lineshapes for emission and absorption
b. gain vs. frequency at fixed electron energy
c. gain vs. electron energy at fixed frequency.

Fig. 3:
a. Spontaneous power transmitted through monochromator at 10.6 μ vs. electron energy.
b. Amplification and absorption of 10.6 μ radiation from CO_2 TEA laser vs. electron energy. The electron energy scale is the same as for 3a. The maximum observed gain was 7% per pass at an electron current of 70 mA.

Fig. 4: Experimental Setup.

Fig. 5:
a. Maximum available calculated gain vs. wavelength for the EH_{11} mode in a 10.2 mm diameter waveguide. The measurement at 10.6 microns is indicated for reference.
b. Maximum available calculated gain per pass vs. wavelength for optimum gaussian optics.

Fig. 6: Princeton-Stanford Electron Storage Ring (1965).

Fig. 7: Schematic representation of Storage Ring Free Electron Laser Oscillator.

Fig. 8: Schematic representation of Free Electron Laser Oscillator using an electron beam from the superconducting accelerator.

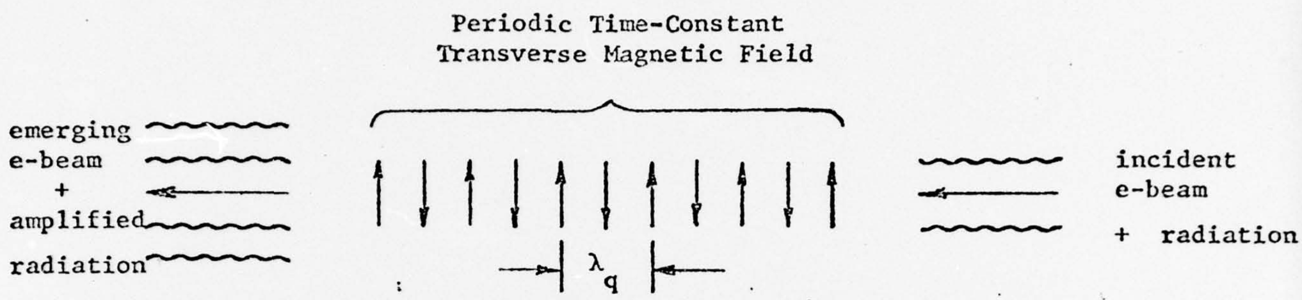
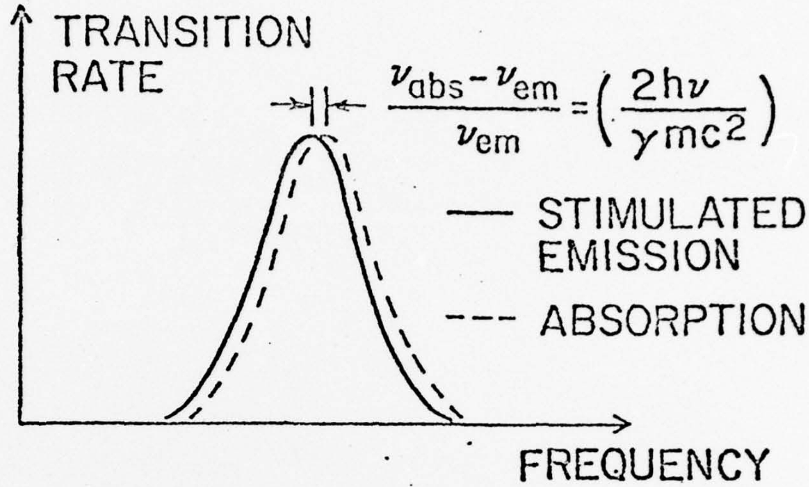
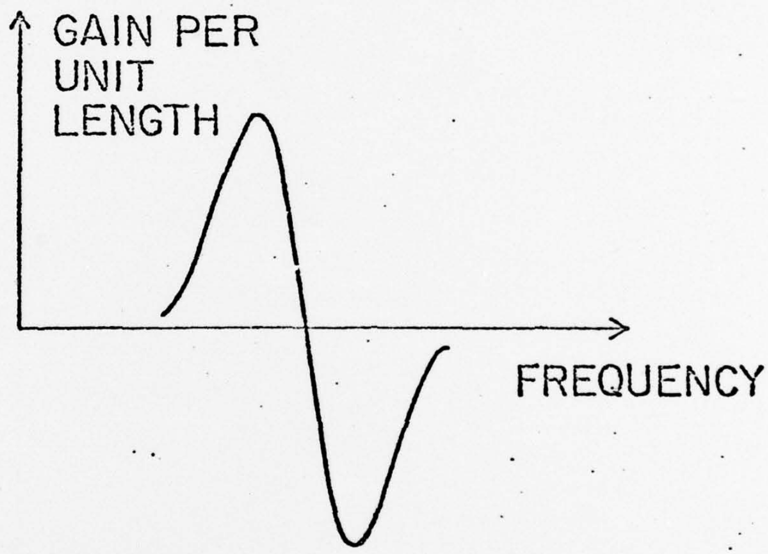

Periodic Time-Constant
Transverse Magnetic Field
emerging
e-beam
+
amplified
radiation
λ_q
incident
e-beam
+ radiation

Figure 1

FIGURE 2a



2b



2c

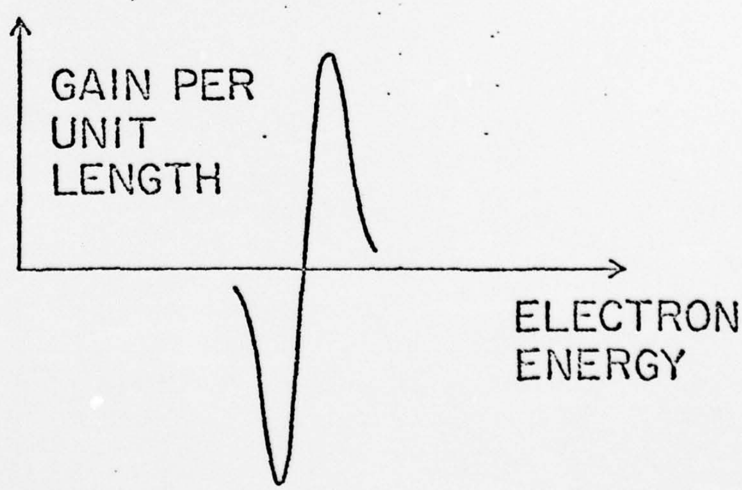
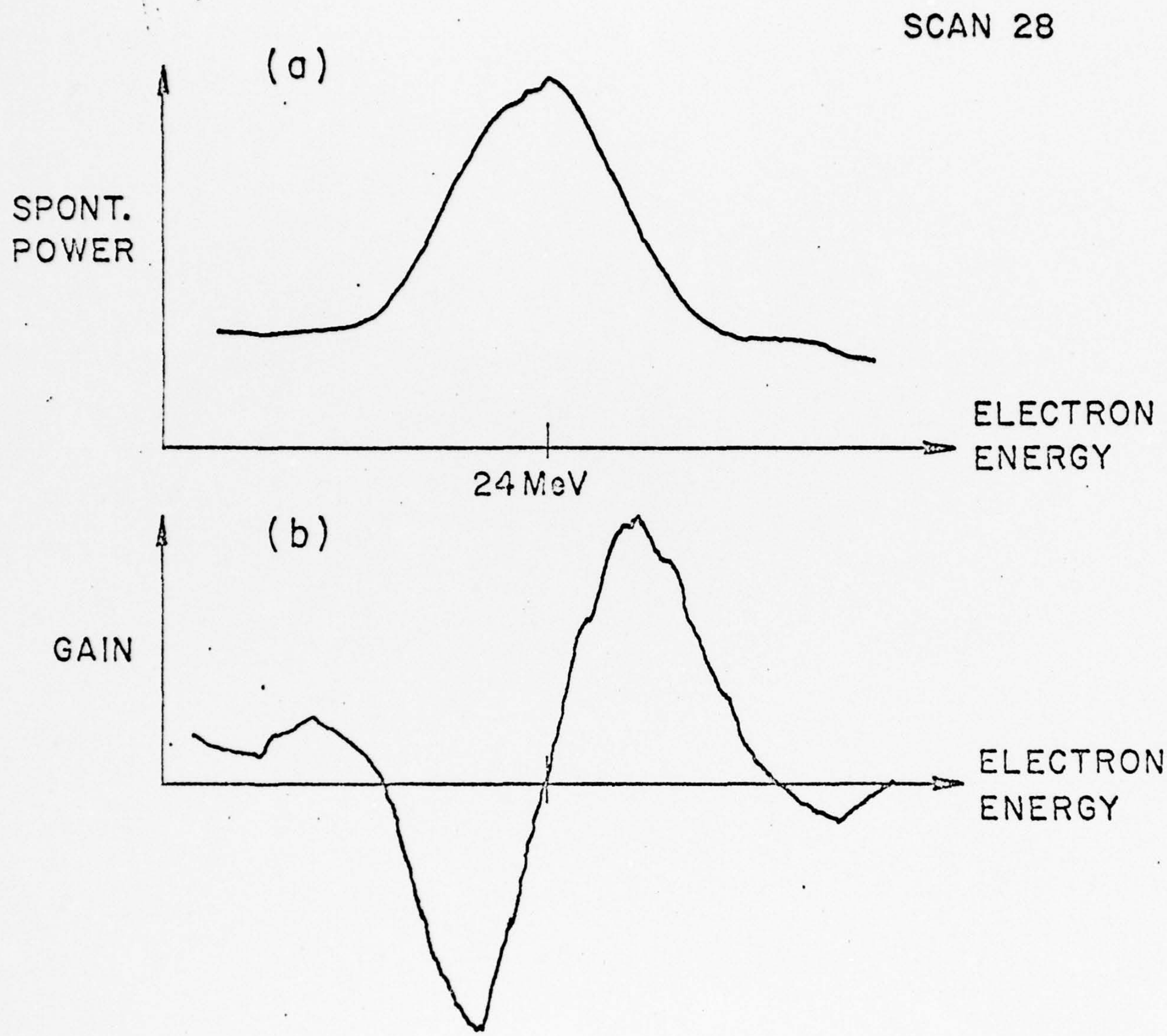


Figure 2



SCAN 28
(a)
SPONT.
POWER
ELECTRON
ENERGY
24 MeV
(b)
GAIN
ELECTRON
ENERGY

Figure 3

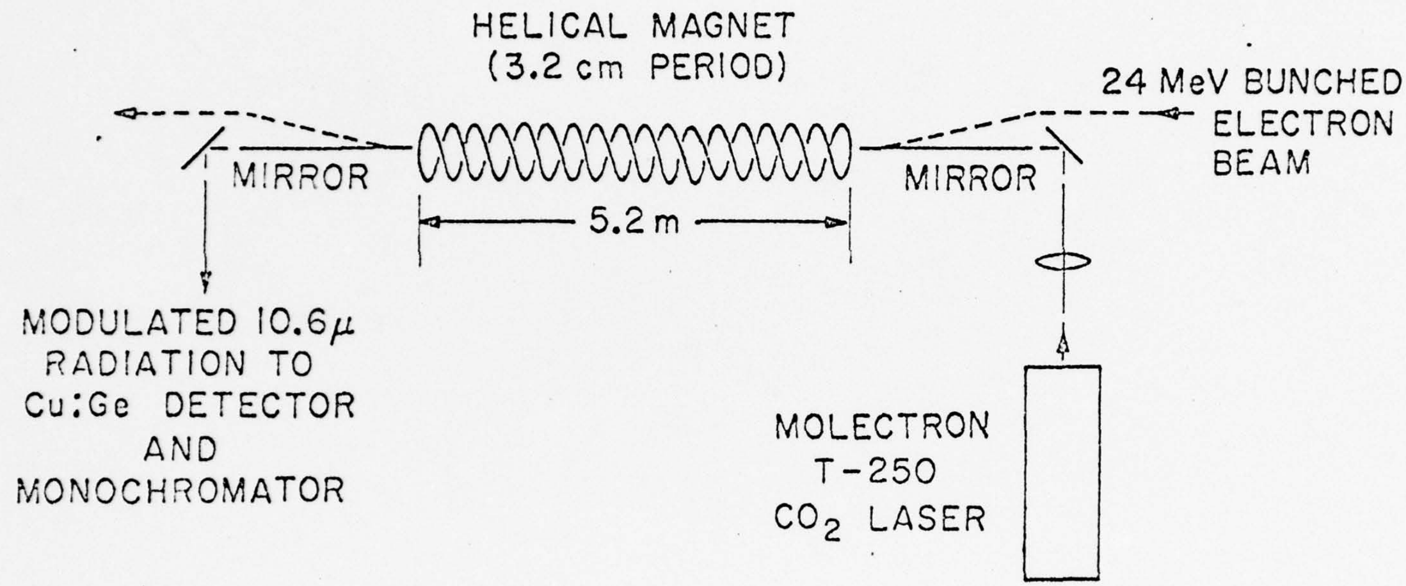

HELICAL MAGNET
(3.2 cm PERIOD)
24 MeV BUNCHED
ELECTRON
BEAM
MIRROR
MIRROR
5.2 m
MODULATED 10.6μ
RADIATION TO
Cu:Ge DETECTOR
AND
MONOCHROMATOR
MOLECTRON
T-250
CO2 LASER

Figure 4

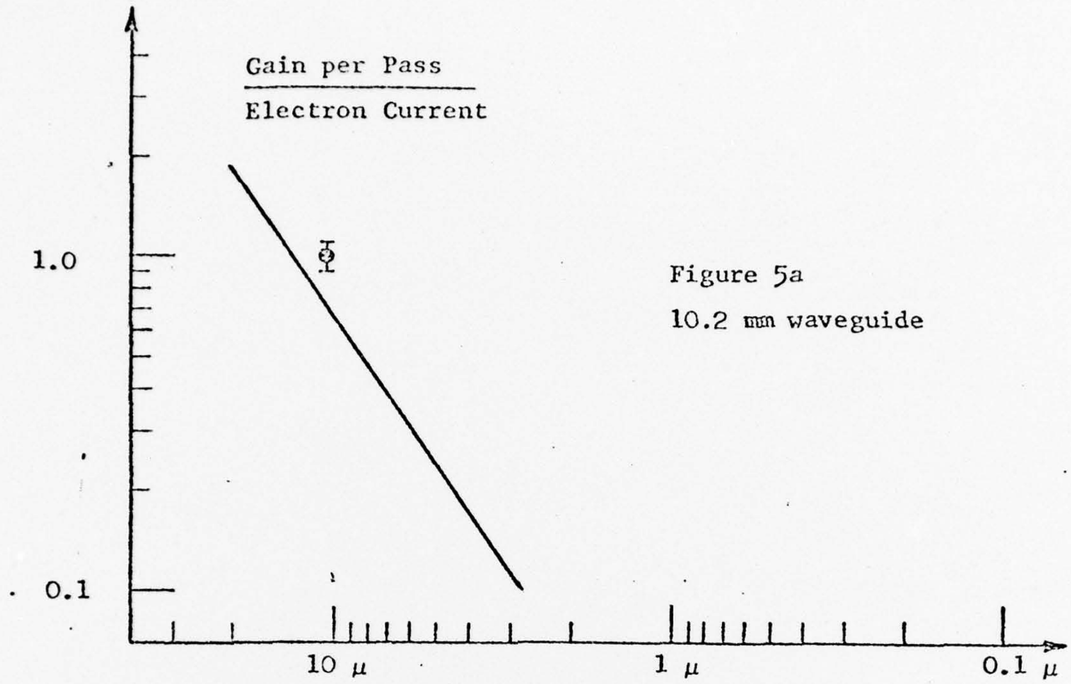


Figure 5a

10.2 mm waveguide

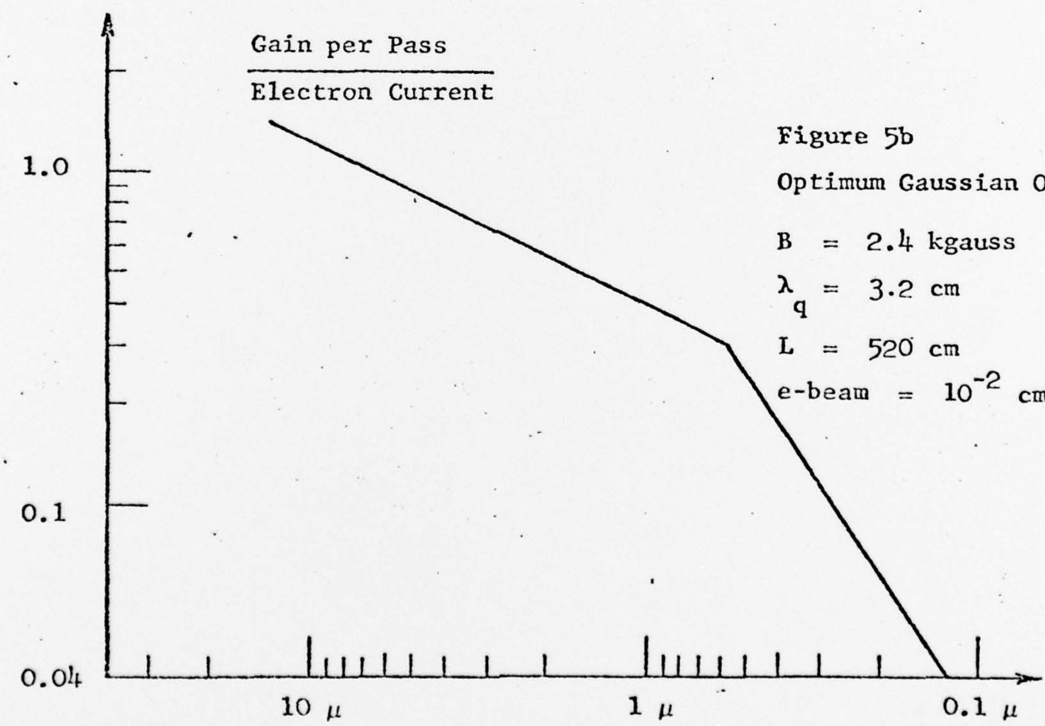


Figure 5b

Optimum Gaussian Optics

$B = 2.4$ kgauss

$\lambda_q = 3.2$ cm

$L = 520$ cm

e-beam $= 10^{-2}$ cm^2

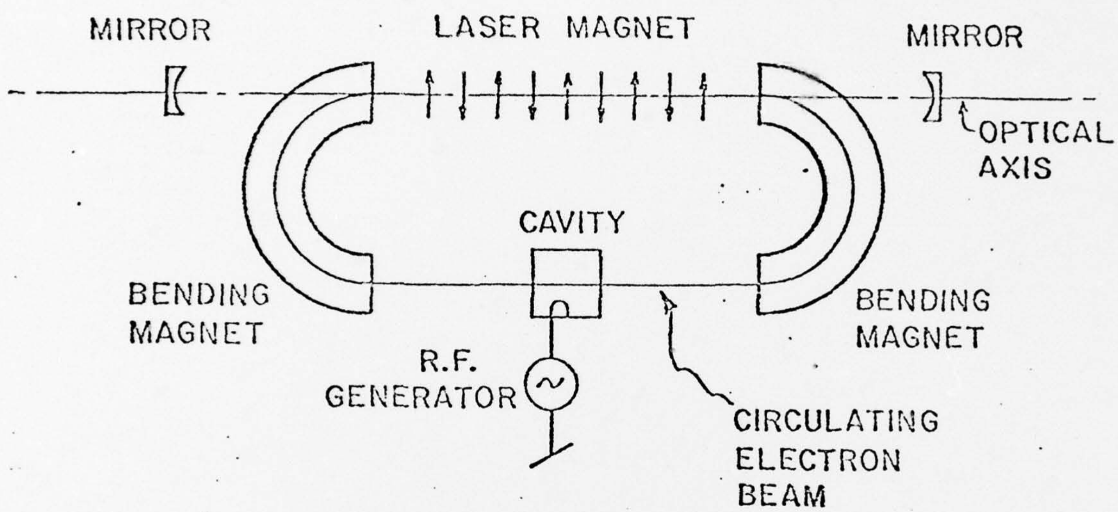


Figure 7

Schematic drawing illustrating the installation of a periodic magnet structure in a straight section of an electron storage ring for a FEL laser oscillator.

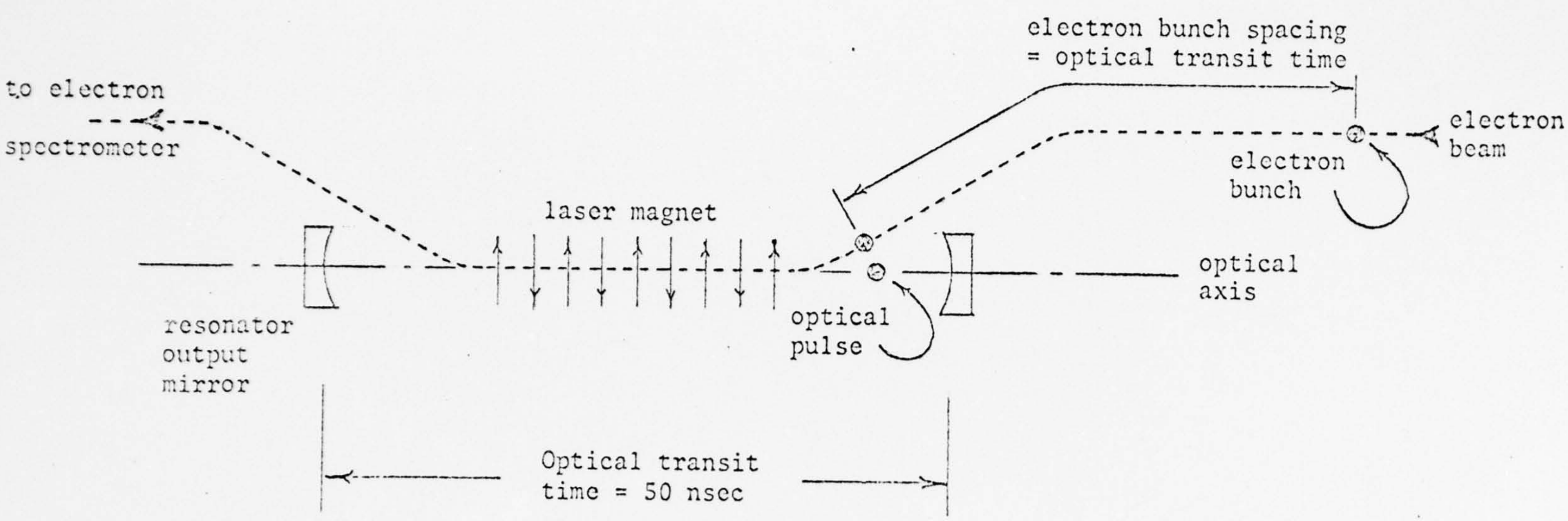


Figure 8: Relationship of the bunch spacing and the optical resonator dimensions for an FEL oscillator using an electron beam from the superconducting accelerator.

Observation of Stimulated Emission of Radiation by Relativistic Electrons in a Spatially Periodic Transverse Magnetic Field*

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Gain has been observed for optical radiation at 10.6 μm due to stimulated radiation by a relativistic electron beam in a constant spatially periodic transverse magnetic field. A gain of 7% per pass was obtained at an electron current of 70 mA. The experiments indicate the possibility of a new class of tunable high-power free-electron lasers.

We have observed the amplification of infrared radiation by relativistic free electrons in a constant, spatially periodic, transverse magnetic field. The experiment was conducted in the W. W. Hansen High Energy Physics Laboratory using an electron beam from the superconducting linear accelerator. The experiment was performed by sending the electron beam through the periodic field and measuring the gain and absorption coefficients for 10.6-μm radiation sent through the field parallel to the electron beam axis.

Radiation emitted within the periodic field is properly termed magnetic bremsstrahlung. Radiation can also be absorbed via the process of inverse bremsstrahlung. The physical effect which makes amplification possible is the difference in wavelength between emission and absorption. The wavelength for emission is slightly longer than the wavelength for absorption. While the difference in wavelength is small, the rates for stimulated emission and absorption are large and net useful gain is predicted at wavelengths to below 1000 Å.

The stimulated emission of bremsstrahlung in a spatially periodic magnetic field was analyzed by Madey and co-workers.[1,2] The physics is related to the problem of stimulated Compton scattering[3] which has been analyzed by Driecer,[4] Pantell, Soncini, and Puthoff,[5] Sukhatme and Wolff,[6] and Kroll.[7] Other free-electron amplifiers have also been proposed. Hirshfield, Bernstein, and Wachtel[8] proposed and developed the cyclotron maser in which a relativistic electron beam moved through a uniform axial field, and Granatstein and co-workers[9,10] at the Naval Research Laboratory have exploited stimulated magneto-Raman scattering to generate high-power submillimeter radiation.

The theory for stimulated bremsstrahlung predicts a correlation between the line shape for spontaneous radiation and the gain. Measurements were therefore made of both the spontaneous radiation and the gain. The experimental apparatus is shown schematically in Fig. 1. The periodic magnetic field was generated by a superconducting right-hand double helix with a 3.2-cm period and a length of 5.2 m. The helix was wound around a 10.2-mm-i.d. evacuated copper tube which enclosed the interaction region. The field due to the helix was transverse and rotated in the plane normal to the axis with the period of winding. A 1-kOe axial guide field was generated by a solenoid wound over the helical magnet.

The electron beam and the infrared radiation were steered to pass through the magnet on the axis. Radiation from a pulsed transverse-excitation-atmospheric CO_2 laser was focused to a 3.3-mm waist at the entrance to the interaction region to excite the EH_{11} wave-guide mode of the 10.2-mm copper tube. Calculations indicate that this configuration couples 98% of the energy in the incident Gaussian beam to the EH_{11} mode.[11]

Radiation emerging from the tube was focused on a fast Santa Barbara Research Corporation copper-doped germanium detector. The electron beam from the superconducting accelerator was bunched and the interaction between the electrons and optical radiation modulated the radiation at the 1300-MHz accelerator operating frequency. The fractional modulation is equal to the gain per pass. The amplitude and phase of the 1300-MHz modulation were recovered by mixing the detec-

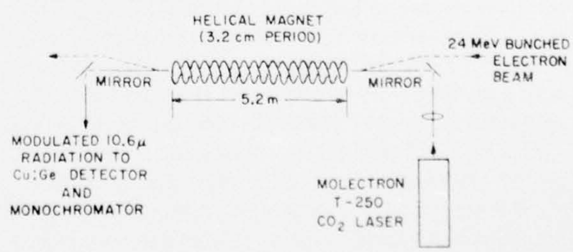

FIG. 1. Experimental setup. The electron beam was magnetically deflected around the optical components on the axis of the helical magnet.

tor output with a signal derived from the accelerator master oscillator. The local oscillator phase was set to maximize the signal due to spontaneous radiation by the electron beam. The relative response of the detector to 1300-MHz modulation was determined by observing the quantum fluctuations in the radiation from a 600° blackbody.

A 1-m Czerny-Turner monochromator was used to analyze the spectral distribution of the spontaneous radiation propagating at angles of up to 1.3 mrad relative to the magnet axis. A helium-cooled germanium bolometer was used with the monochromator to detect the spontaneous radiation.

Observation of the spontaneous radiation and the gain included measurement of (1) the spectral distribution and polarization of the spontaneous radiation, (2) the magnitude of the gain, and (3) the dependence of the gain on the electron energy, the polarization of the stimulating radiation fields, the electron current, the magnetic field, and the optical power density.

According to theory, the wavelengths for emission and absorption are given by

$$\lambda = \frac{\lambda_q}{2\gamma^2}\left[1 + \left(\frac{1}{2\pi}\right)^2 \frac{\lambda_q^2 r_0}{mc^2} B^2\right]\left(1 \pm \frac{h\nu}{\gamma mc^2}\right), \qquad (1)$$

where r_0 is the classical electron radius (cm), γmc^2 is the electron energy (ergs), λ_q is the magnet period (cm), and B is the transverse magnetic field (G). Equation (1) is for a helical magnetic field and for radiation parallel to the electron beam axis. The equation is correct to lowest order in $1/\gamma$ and $h\nu/\gamma mc^2$. No harmonics are present in the spectrum for radiation along the axis. Polarization is determined by the helix symmetry.

The minimum theoretical linewidth for spontaneous emission is established by the length of the magnet. For the magnet in the experiment the minimum $1/e$ half-linewidth ($\Delta\nu/\nu$) is 0.3%. The broadening due to the finite length is homogeneous. There are also inhomogeneous effects, including the spread in energy and angular divergence of the electron beam and the variation in magnetic field over the cross section of the beam.

Figure 2(a) indicates the observed dependence on the electron energy of the spontaneous power at 10.6 μm. The monochromator was set at 10.6 μm while the electron energy from the superconducting accelerator was swept through a range of approximately 2% in the vicinity of 24 MeV. The resolution of the monochromator was 0.2%. The

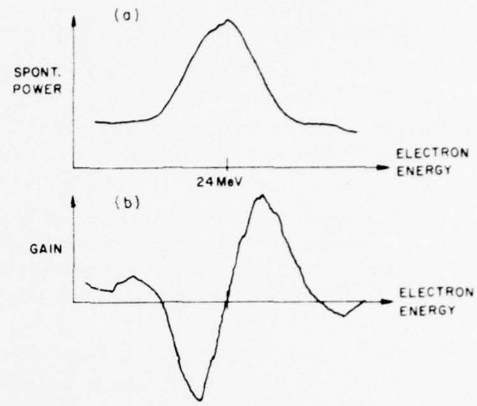

FIG. 2. (a) The spontaneous power at 10.6 μm as a function of the electron energy. (b) The amplitude and phase of the modulation imposed on the 10.6-μm optical radiation from the CO_2 laser. Amplification corresponds to a positive signal. The instantaneous peak gain attained a value of 7% per pass. The helix field amplitude was 2.4 kG and the instantaneous peak electron current was 70 mA. The electron energy was swept through a small range in the vicinity of 24 MeV. The full width in energy (half-width in wavelength) at the $1/e$ points in (a) is 0.4%. The power density of the 10.6-μm radiation in (b) was 1.4×10^5 W/cm^2.

$1/e$ half-width of the spectrum ($\Delta\nu/\nu$) is 0.4%. The linewidth is close to the theoretical minimum. No harmonics were observed. The magnetic field was 2.4 kG. The instantaneous spontaneous power radiated into the 5×10^{-6}-sr acceptance of the detection system was 4×10^{-6} W at an instantaneous peak current of 70 mA. The radiation was right-circularly polarized.

Figure 2(b) indicates the dependence of the gain on electron energy. The energy scale is the same as for Figure 2(a). The trace shows the phase and amplitude of the 1300-MHz modulation imposed on the 10.6-μm optical radiation from the CO_2 laser. This signal is proportional to the time-averaged gain (or absorption) per pass. The instantaneous peak gain is equal to the time-averaged gain divided by the electron-beam duty cycle, i.e., the ratio of the electron bunch length to the bunch period (0.56%). The instantaneous peak gain per pass in Fig. 2(b) reaches 7%. The instantaneous peak current was 70 mA.

Figures 2(a) and 2(b) illustrate the correlation between the gain and the line shape for spontaneous emission. Note that (1) the gain falls to zero at the peak of the spontaneous spectrum, (2) there is a net gain on the high-energy side and net absorption on the low-energy side of the line-shape for spontaneous emission, and (3) the maximum values of gain and absorption occur at the points of inflection of the spontaneous spectrum.

Figure 2(b) was made using right-circular polarization. The measured gain was zero for left-circular polarization. The observed gain for linear polarization was half the gain for right-circular polarization. The magnitude of the gain was observed to be a linear function of the electron current over a range of 5 to 70 mA.

Finally, the gain was measured at optical power densities ranging from 100 to 1.4×10^5 W/cm^2. The magnitude of the gain and the dependence of the gain on the electron energy were observed to be independent of the optical power density over this range. The stimulated power radiated by the electrons reached 4×10^3 W in these measurements. This power was 10^9 times larger than the spontaneous power measured with the same electron current and corresponds to an energy loss of 60 keV per electron in passage through the helix.

According to Madey, Schwettman, and Fairbank[2] the gain due to stimulated bremsstrahlung is given by

$$G=\frac{10\,(\log_{10}e)}{2\pi(\pi)^{1/2}}\left(\frac{r_0^{\,2}}{hc}\right)\lambda^2\lambda_q^{\,2}B^2\rho_eF_f\left(\frac{\Delta\nu}{\nu}\right)^{-1}\left\{\exp\left[-\frac{(\delta\nu/\nu)^2}{(\Delta\nu/\nu)^2}\right]-\exp\left[-\frac{[(\delta\nu/\nu)-(2h\nu/\gamma mc^2)]^2}{(\Delta\nu/\nu)^2}\right]\right\}\ \mathrm{dB\ cm^{-1}}, \tag{2}$$

where ρ_e is the density of electrons in the electron beam (cm^{-3}); λ and ν are the operating wavelength and frequency (cm and Hz, respectively); $\Delta\nu$ is the $1/e$ half-linewidth for spontaneous emission (Hz); $\delta\nu$ is the difference between the operating frequency and the emission line center (Hz); and F_f, the filling factor, is the ratio of the squares of the radii of the electron beam and the radiation field. The filling factor is unity if the electron beam radius exceeds the radius of the radiation field.

The gain equation is for a helical magnetic field and for circularly polarized radiation propagating parallel to the electron beam. Stimulated emission is possible only for that component of the stimulating radiation field which matches the polarization of the spontaneous radiation. The derivation assumes a small signal and a weak magnetic field.

The first exponential within the braces is due to stimulated emission and the second to absorption. The line shape for stimulated emission and absorption have the same form as the line shape for spontaneous emission (a Gaussian line shape was assumed). For optical photons $2h\nu/\gamma mc^2 \ll \Delta\nu/\nu$ and the difference between the two exponentials is small. The gain is then proportional to the derivative of the line shape for spontaneous emission and becomes independent of h. The derivative relationship is nicely illustrated by the traces in Fig. 2. The maximum available theoretical gain is

$$G=\frac{20\log_{10}e}{\pi}\left(\frac{1}{e\pi}\right)^{1/2}\left(\frac{r_0^{\,2}}{mc^2}\right)\lambda^{3/2}\lambda_q^{\,3/2}B^2\rho_e\left(\frac{\Delta\nu}{\nu}\right)^{-2}F_f\ \mathrm{dB\ cm^{-1}}. \tag{3}$$

The functional form of the gain is constrained by symmetry and dimensionality. This is important because the constraints establish scaling laws independent of the approximations used in computation. Given that the gain arises from a second-order process and is independent of h, the small-signal weak-field gain must be linear in the electron current, quadratic in the magnetic field, and vary as $\lambda^{3/2}$ for unity filling factor as in Eq. (3). The dependence on wavelength is modified when the filling factor is less than 1: For a fixed interaction length and optimal Guassian optics the filling factor scales as λ^{-1} and the gain scales as $\lambda^{1/2}$.

For the experimental conditions and with the assumption of an effective area of 0.33 cm^2 for the EH$_{11}$ mode, the calculated gain attains a maximum value of 5% for the 5.2-m interaction length as opposed to 7%, the observed value. The significance of the difference is not yet established; however, random errors in the measurement were negligible and the difference is believed to exceed the systematic error.

These measurements have important device implications. Lasers based on the stimulated emission of bremsstrahlung have a potential for continuously tunable operation at high power. The current available from existing electron machines indicates the possibility of laser operation from the infrared to the ultraviolet. The instantaneous peak current from the superconducting accelerator can be raised to the ampere level by reducing the duty cycle, and circulating peak currents in excess of 10 A have been obtained in electron storage rings.[12]

Use of a storage ring would be particularly attractive because the rf accelerating field for the ring would have to supply only the energy actually transformed to radiation in the periodic field. The overall efficiency of such a system thus would not be limited to the fraction of the electrons' energy convertible to radiation in a single pass through the interaction region. The feasibility of the idea hinges on the form of the electrons' phase-space distribution after passage through the periodic field, a subject currently under study.

An electron current of the order of 1 A at 240 MeV would be sufficient for laser operation at 1000 Å for a 1-mm^2 electron-beam cross section. The measurements indicate that 0.2% of the electrons' energy can be converted to radiation in the periodic field without evidence of saturation; the corresponding power output for a 1-A, 10^8-eV electron beam would exceed 10^5 W.

We gratefully acknowledge the contributions of the Hansen Laboratory personnel and others who have assisted in this effort.

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*Work supported in part by the U. S. Air Force Office of Scientific Research.

[1]J. M. J. Madey, J. Appl. Phys. 42, 1906 (1971).

[2]J. M. J. Madey, H. A. Schwettman, and W. M. Fairbank, IEEE Trans. Nucl. Sci. 20, 980 (1973).

[3]While the published Compton-scattering gain formulas can be reduced to a common functional form, the numerical factors are such that the predicted gains differ by up to two orders of magnitude.

[4]H. Dreicer, Phys. Fluids 7, 735 (1964).

[5]R. H. Pantell, G. Soncini, and H. E. Puthoff, IEEE J. Quantum Electron. 4, 905 (1968).

[6]V. P. Sukhatme and P. A. Wolff, J. Appl. Phys. 44, 2331 (1973).

[7]N. Kroll, in Stanford Research Institute Technical Report No. JSR-74-1, 1975 (unpublished), p. 74.

[8]J. L. Hirshfield, I. B. Bernstein, and J. M. Wachtel, IEEE J. Quantum Electron. 1, 237 (1965).

[9]V. L. Granatstein, M. Herndon, R. K. Parker, and S. P. Schlesinger, IEEE Trans. Microwave Theory Tech. 22, 1000 (1974).

[10]P. Sprangle, V. L. Granatstein, and L. Baker, Phys. Rev. A 12, 1697 (1975).

[11]R. L. Abrams, IEEE J. Quantum Electron. 8, 838 (1972).

[12]The Stanford-Princeton ring stored a peak current of 15 A at 300 MeV [W. C. Barber, High Energy Physics Laboratory Report No. 350 (unpublished)]. The SPEAR ring at SLAC has stored a peak current in excess of 100 A [H. Winick, SLAC Report No. 1349 (unpublished)].